Bivergent thrust wedges surrounding oceanic island arcs: Insight from observations and sandbox models of the northeastern Caribbean plate

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ABSTRACT

At several localities around the world, thrust belts have developed on both sides of oceanic island arcs (e.g., Java-Timor, Panama, Vanuatu, and the northeastern Caribbean). In these localities, the overall vergence of the backarc thrust belt is opposite to that of the forearc thrust belt. For example, in the northeastern Caribbean, a north-verging accretionary prism lies to the north of the Eastern Greater Antilles arc (Hispaniola and Puerto Rico), whereas a south-verging thrust belt called the Muertos thrust belt lies to the south. Researchers have attributed such bivergent geometry to several processes, including: reversal of subduction polarity; subduction-driven mantle flow; stress transmission across the arc; gravitational spreading of the arc; and magmatic inflation within the arc. New observations of deformational features in the Muertos thrust belt and of fault geometries produced in sandbox kinematic models, along with examination of published studies of island arcs, lead to the conclusion that the bivergence of thrusting in island arcs can develop without reversal of subduction polarity, without subarc mantle flow, and without magmatic inflation. We suggest that the Eastern Greater Antilles arc and comparable arcs are simply crustal-scale bivergent (or "doubly vergent") thrust wedges formed during unidirectional subduction. Sandbox kinematic modeling suggests, in addition, that a broad retrowedge containing an imbricate fan of thrusts develops only where the arc behaves relatively rigidly. In such cases, the arc acts as a backstop that transmits compressive stress into the backarc region. Further, modeling shows that when arcs behave as rigid blocks, the strike-slip component of oblique convergence is accommodated entirely within the prowedge and the arc—the retrowedge hosts only dip-slip faulting ("frontal thrusting"). The existence of large retrowedges and the distribution of faulting in an island arc may, therefore, be evidence that the arc is relatively rigid. The rigidity of an island arc may arise from its mafic composition and has implications for seismic-hazard analysis.

INTRODUCTION

It has long been recognized that convergence in continent-continent collisions and in continental subduction zones produces bivergent (or doubly vergent) orogens (e.g., Burchfiel and Davis, 1975; Willett et al., 1993). Such orogens are so named because the overall vergence, or transport direction, of the thrust belt on one side of the orogen is opposite to that of the thrust belt on the other side. In a general sense, bivergent orogens consist of three zones: (1) the prowedge, consisting of a thrust system building on the downgoing plate; (2) a retrowedge, consisting of a thrust system propagating into the foreland of the overriding plate; and (3) a central uplift, consisting of the wedge's internal zone that rises between the prowedge and retrowedge (Willett et al., 1993; Beaumont and Quinlan, 1994; Fig. 1A). The material incorporated in bivergent orogens is primarily crustal, therefore such orogens are also called "bivergent crustal wedges."

There are several examples of island arcs in which a thrust belt with vergence opposite to that of the accretionary prism develops in the backarc region, so that bivergent thrusting involves the *entire* island arc (e.g., Banda, Vanuatu, and Panama arcs; Fig. 2). The Eastern Greater Antilles arc (Hispaniola and Puerto Rico) of the northeastern Caribbean illustrates this geometry. A north-verging accretionary prism lies between the Puerto Rico Trench in the forearc region, while a south-verging thrust belt, called the Muertos thrust belt, lies between the arc and the Muertos Trough in the backarc region (Fig. 3). The issue of whether such island arcs are bivergent crustal wedges, similar to those developed during Alpine-type continental collisions, has proven to be problematic. The literature attributes the existence of a backarc thrust belt to different phenomena, such as: subduction reversal (Dewey and Bird, 1970; Byrne et al., 1985); converging mantle flow beneath the arc (Conrad et al., 2004); gravitational spreading of the thickened crust in the arc (Silver et al., 1983; Breen et al., 1989); inflation of the arc by magmatic intrusion (Hamilton, 1979); and stress propagation

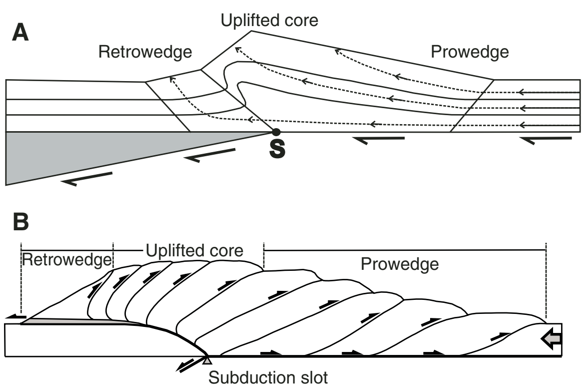

Figure 1. (A) Shape of bivergent wedge and material trajectory from numerical models (after Willett et al., 1999). S—Singularity point. (B) Geometry of bivergent wedge simplified from results of oblique convergence in sandbox models (modified from McClay et al., 2004).

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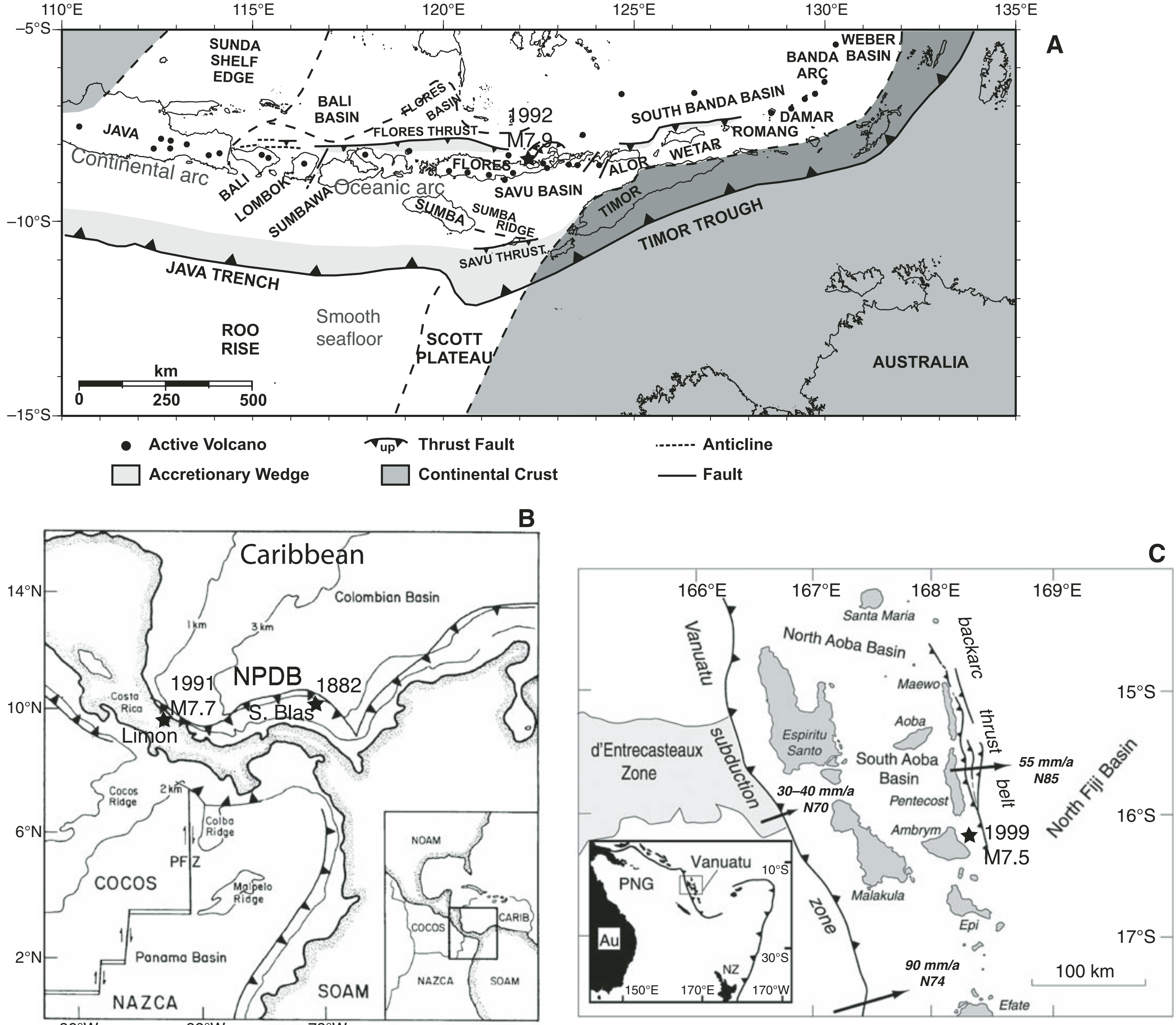

Figure 2. Location maps of bivergent wedges around island arcs. (A) Java-Timor Trench (modified from Silver et al., 1983). (B) Panama and North Panama deformation belt (NPDB) (modified from Suárez et al., 1995). PFZ—Panama fracture zone. (C) New Hebrides Trench near Vanuatu (modified from LaGabrielle et al., 2003). PNG—Papua New Guinea; NZ—New Zealand, AU—Australia.

across the arc and into the backarc in response to collision in the forearc (Silver et al., 1983).

The apparent lack of consensus concerning the origin of backarc thrust systems led us to address the following three questions: (1) Are backarc thrust systems the retrowedge part of a bivergent crustal wedge, formed in response to transmission of compressive stress across the crust of the arc, or are they a manifestation of subduction reversal or of upper-mantle flow? (2) What mechanical role does the volcanic arc (or extinct arc) serve during the development of a backarc thrust belt? (3) How does oblique convergence affect the kinematics of backarc thrusting? To address these questions, we utilized analysis of multibeam bathymetric maps and seismic-reflection profiles in the vicinity of the northeast Caribbean arc, we produced simple sandbox kinematic models simulating relative motions of crustal components in the northeast Caribbean, and we examined published studies of island arcs worldwide.

This paper begins by presenting an analysis of the Eastern Greater Antilles arc based on multibeam and seismic-reflection studies. We then provide a brief review of published observations from comparable island arcs elsewhere. Finally, we describe the results of simple sandbox models designed to illustrate the map-view kinematics of bivergent thrusting. Our observations lead us to suggest that the Eastern Greater Antilles arc is a bivergent crustal wedge formed due to stress transmission across the arc from

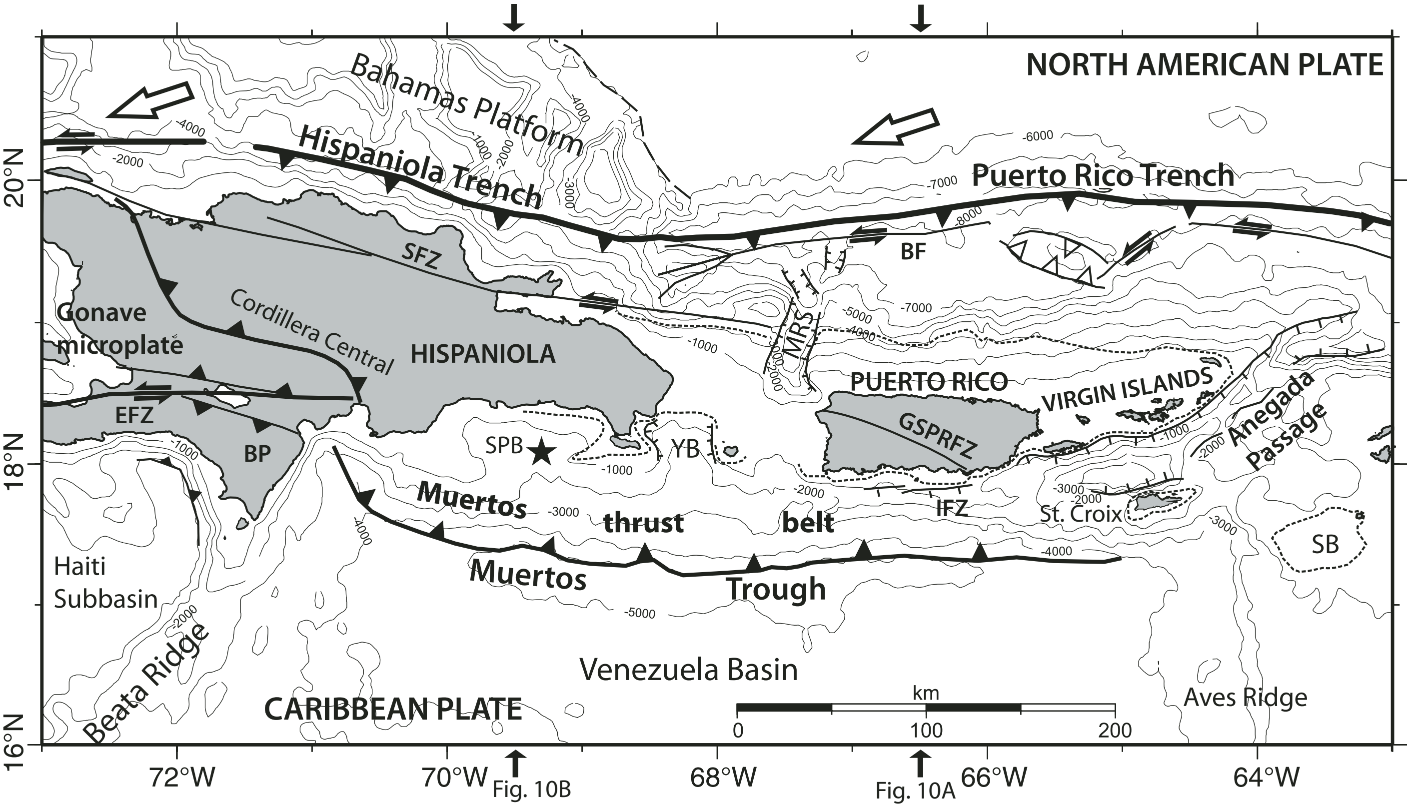

Figure 3. Regional tectonic setting of northeastern Caribbean plate. Contours show the satellite bathymetry data gridded at 2 min interval (Smith and Sandwell, 1997). Thick arrows—relative convergence direction between North American and Caribbean plates. Oligocene-Pliocene carbonate platform extension is outlined by dotted line (van Gestel et al., 1998). Star corresponds with the location of the Ms = 6.7 event calculated by Byrne et al. (1985). BF—Bunce fault, BP—Bahoruco Peninsula; EFZ—Enriquillo fault zone, SFZ—Septentrional fault zone, GSPRFZ—Great Southern Puerto Rico fault zone, IFZ—Investigator fault zone, MRS—Mona Rift system, SB—Saba Bank, SPB—San Pedro Basin, YB—Yuma Basin.

the subduction zone, that the existence of backarc thrusting in the Muertos thrust belt does not require subduction of the Caribbean plate beneath the Eastern Greater Antilles arc, and that the kinematics of the belt argue against its association with mantle flow. We argue that a similar interpretation also applies to several other oceanic island-arc systems around the world (Fig. 2). Our sandbox modeling also emphasizes that a broad backarc thrust belt containing an imbricate fan of thrusts only develops where an oceanic island arc behaves as a relatively rigid block and can transmit compressive stress to the backarc region. If the arc behaves rigidly, the strike-slip component of oblique convergence is accommodated in the forearc; relatively few thrust faults develop within the arc itself; and only perpendicular convergence occurs in the backarc. Notably, the bivergent crustal wedge model of island arcs has implications for seismic-hazard assessment of arcs because it provides a basis for predicting the distribution of faulting.

OBSERVATIONS FROM THE NORTHEASTERN CARIBBEAN

Background: Geologic Setting of the Northeastern Caribbean Plate

The Greater Antilles volcanic arc, which extends from Cuba to the Virgin Islands, was formed during the Cretaceous and Early Tertiary as the North American plate subducted southwesterly beneath the Caribbean plate (Pindell and Barrett, 1990). Beginning at 49 Ma, relative plate motion changed to a more easterly direction (~250°), resulting in a cessation of arc volcanism, and in highly oblique subduction with a large component of left-lateral strike-slip. The direction of plate convergence has been fairly constant since 49 Ma, as indicated by the length and trend of transform faults bordering Cayman Trough between Cuba and Honduras (e.g., Draper et al., 1994). Presently, normal-thickness, 85–125 Ma oceanic crust of the Atlantic subducts under Puerto Rico and the Virgin Islands at a rate of 18–20 mm/a (e.g., Mann et al., 2002). Adjacent to the Hispaniola Trench, the Bahamas Platform block of significantly thicker crust with continental affinity has moved into the trench (Freeman-Lynde and Ryan, 1987). Thrust earthquakes occur along a shallowly dipping (~20°) zone under northern Hispaniola (Dolan and Wald, 1998), indicating that convergence still takes place across this boundary, so that Hispaniola is currently thrusting over the Bahamas Platform.

The on-land geology of Hispaniola and Puerto Rico in the eastern Greater Antilles is complex (see reviews by Draper et al., 1994; Larue, 1994). A Cretaceous to early Eocene arc assemblage consisting of accretionary prism sediments, arc volcanics and intrusives, and ophiolites forms the basement of Hispaniola. Eocene and younger clastics and carbonates have accumulated over this arc-assemblage basement. The last arc-building phase recorded in Puerto Rico occurred in the early Tertiary. In the late Eocene and Oligocene, several kilometers of uplift, as well as rotation around a vertical axis, affected the island (Larue, 1994). In post-Oligocene time, a carbonate platform was formed over the arc complex. Recent exhumation of mid- or lower-crustal rocks has not occurred in the eastern Greater Antilles.

The Muertos thrust belt forms the southern margin of Hispaniola and Puerto Rico and is ~650 km long (Fig. 3). The boundary between the thrust system and the exposed floor of the Caribbean plate is a linear depression known as the Muertos Trough (Fig. 4), in which water depths reach 5580 m. The age of initial convergence across the Muertos Trough is unknown. Early Miocene and older sedimentary rocks, which cover the Caribbean plate, appear to be in the footwall, beneath the thrust belt's basal detachment (Fig. 5), whereas younger sediments may be incorporated into the thrust belt itself.

The Caribbean plate's interior includes regions of anomalously thick oceanic crust—locally, it is over twice as thick as that of the Atlantic Ocean crust north of Puerto Rico. Formation of thick Caribbean crust probably reflects production of flood basalts in a large igneous province (e.g., Burke et al., 1978; Driscoll and Diebold, 1998). In the region south of Hispaniola, an asymmetric NNE-trending high, known as the Beata Ridge, brings Caribbean crust up to shallower depths. The Beata Ridge appears to be underlain by somewhat thicker crust than that of the adjacent Venezuelan Basin to the east, and it appears to be bounded on its southeastern edge by faults (Driscoll and Diebold, 1998; Mauffret and Leroy, 1999).

Observations from the Muertos Trough and Muertos Thrust Belt

Bathymetric digital elevation models (DEM) with a spatial resolution of 50 m, produced during recent multibeam bathymetry surveys of the Muertos Trough and Muertos thrust belt, reveal the detailed structure of this area (Fig. 4). Vertical cross sections through this region are provided by 10 newly acquired high-resolution multichannel profiles, 8 reprocessed profiles (obtained from the seismic-data library of the University of Texas), and 7 scanned analog single-channel seismic lines, supplied by A. Mauffret. These data, together with published core and dredge data (Nagle et al., 1978), allow interpretation of the Muertos thrust system and help distinguish among proposed mechanisms for its formation.

The Muertos thrust belt can be divided into three provinces. In the Lower Slope Province, active imbricate thrusts break the seafloor surface. This thrusting, along with thrust-related folding, has yielded distinct, <20-km-long and <5-km-wide ridges that trend roughly parallel to contours of the slope (Fig. 5). The Lower Slope Province widens significantly from 4 to

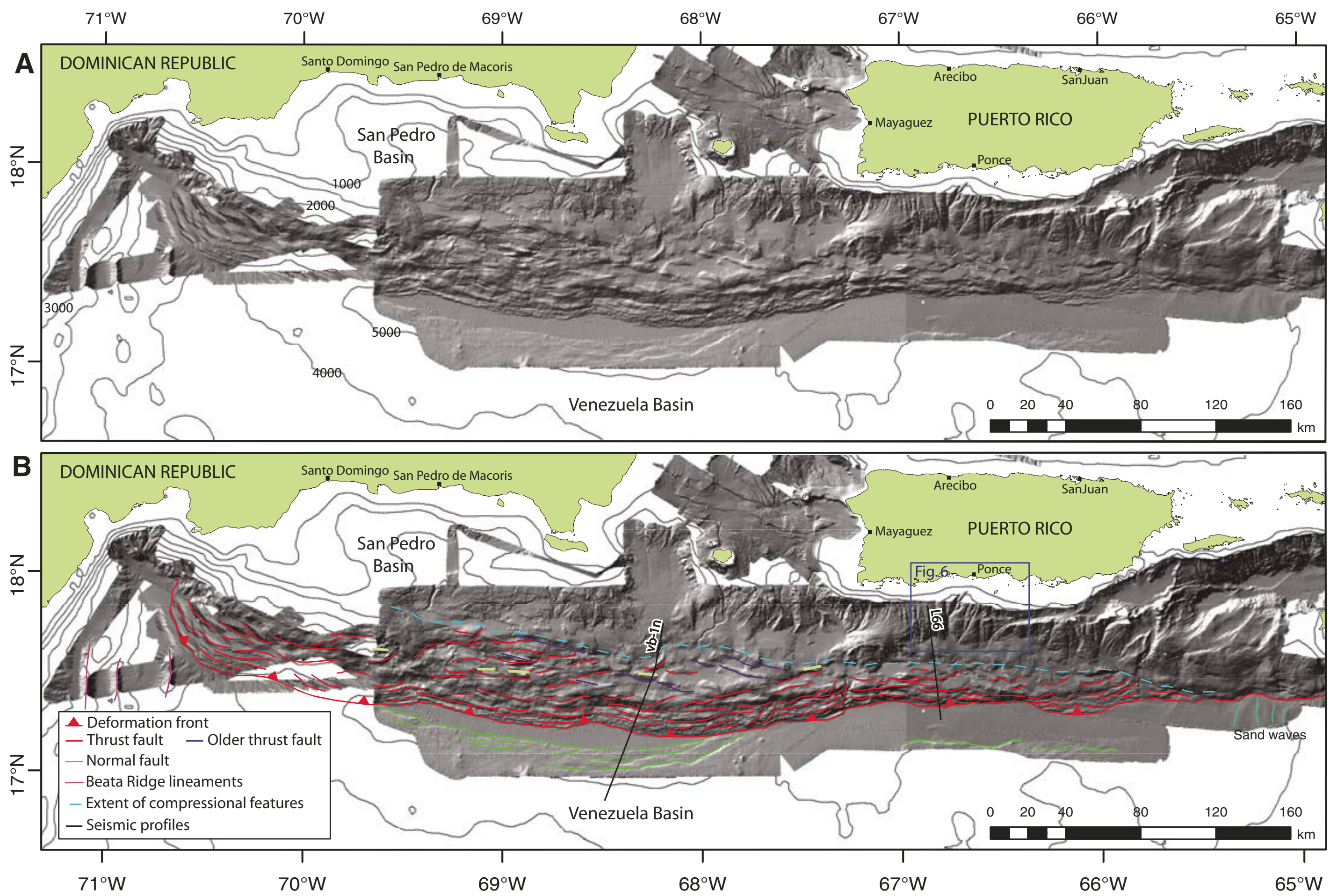

Figure 4. (A) Shaded relief bathymetry map illuminated from northwest, gridded at 150 m grid size. Sources of multibeam bathymetry data are SeaCarib (Mauffret and Leroy, 1999), Geoprico-Do (Carbó et al., 2005), and U.S. Geological Survey (USGS) 2006 Tsucar and USGS 2007 Mona Passage cruises. (B) Same as A, overlain by interpretation. Solid lines—locations of seismic profiles in Figure 5. Rectangle—location of Figure 6.

10 km south of Puerto Rico to ~25 km south of the Dominican Republic (Figs. 4 and 5). In the Middle Slope Province, slope-surface ridges are subdued, suggesting that imbricate thrusting is less active. Some of the subdued ridges trend ~20° more northwesterly than those of the Lower Slope Province (purple lines in Fig. 4), and thus they may indicate that the transport direction of thrusting changed as thrusting propagated southward with time. The combined Lower Slope and Middle Slope Provinces, south of Puerto Rico, are 18–22 km wide and increase in width to 45 km south of the Dominican Republic (dashed blue line in Fig. 4). The Upper Slope Province of the Muertos thrust belt is underlain by island-arc basement and accreted sedimentary rocks buried by carbonate-platform and slope sediments. In general, thrusting in the Upper Slope Province appears to have become inactive. However, in the vicinity of longitude 69.2°W, high-angle north-dipping thrust faults (as seen in reprocessed seismic lines from Ladd et al., 1981) cut the surface of the Upper Slope Province. These faults lie above the 1984 M_s 6.7 earthquake (star in Fig. 3), and their presence may indicate that active faulting delineates the southern edge of the San Pedro Basin, 75 km north of Muertos Trough.

Normal faults subparallel to the deformation front are exposed on the Caribbean plate seafloor within Muertos Trough. These faults extend to a distance of ~30 km south of the frontal thrust of the Muertos thrust belt, and they have produced an axial low reaching a depth of 5580 m in the region west of longitude 68.5°W (Fig. 4). East of longitude 68.5°W, these faults curve northward, and between longitude 68°W and 67.7°W, they terminate at the thrust front. Similar normal faults have been observed on many subducting plates to a distance of 50–60 km oceanward of the trench, and they are interpreted to be a deformational response to tensile flexural stresses resulting from the bending of the subducting plate (Bodine and Watts, 1979; Ranero et al., 2005). Notably, the normal faults south of the Muertos Trough are best developed where the Lower and Middle Slopes Provinces of the Muertos thrust belt are particularly wide—the faults gradually terminate along strike to the east, where the retrowedge is narrower. This relation suggests that the normal faulting may have been amplified by loading when retrowedge thrust sheets loaded the Caribbean plate.

At the western end of the Muertos Trough, fault traces and the thrust front of the Muertos thrust belt change trend, curving from east-west to north-south over a distance of ~30 km (Fig. 4). This change occurs where the thrust belt terminates against three north-south–trending ridges that lie offshore and to the east of the Bahoruco Peninsula of southern Hispaniola. The Bahoruco Peninsula and the ridges represent the northernmost end of the Beata Ridge (Fig. 3; Mauffret and Leroy, 1999). Thus, the curvature of the Muertos thrust belts here suggests that the Beata Ridge has acted as an indenter that pushed into Hispaniola (cf. Marshak, 2004). Indentation by the Beata Ridge may also explain why the highest portion of Hispaniola's Cordillera Central, where elevations reach 3 km, lies inboard of the Beata Ridge and why thrust faults on the island itself curve adjacent to this highland (Hernaiz Huerta and Pérez-Estaún, 2002; Heubeck and Mann, 1991; Mercier de Lepinay et al., 1988).

In detail, thrust-fault traces of the Muertos thrust belt are segmented along strike into 50–90-km-long segments that are slightly convex to the south. These curves are symmetrical salients, the presence of which may reflect interactions between the thrust system and basement highs on the underlying Caribbean plate. The fact that the salients are symmetrical suggests that the transport direction within the Muertos thrust system is southward perpendicular to the regional trend of the belt.

Active strike-slip faulting has *not* been identified within the southern insular slopes of Puerto Rico and Hispaniola, despite highly oblique motion between the Caribbean and North American plates (Manaker et al., 2008). This statement derives from the following three observations. First, the Enriquillo fault, the only fault with documented strike-slip displacement in the southern part of the eastern Greater Antilles, terminates west of the Muertos Trough and thus does not cut the Muertos thrust system. Second, the Investigator fault (Garrison, 1969), which is manifested on bathymetric maps as a system of several east-west–trending subparallel lineaments crossing the Upper Slope Province south of Puerto Rico (Fig. 4), does not offset submarine canyons and thus cannot currently accommodate strike-slip motion (Fig. 6). In fact, seismic profiles suggest

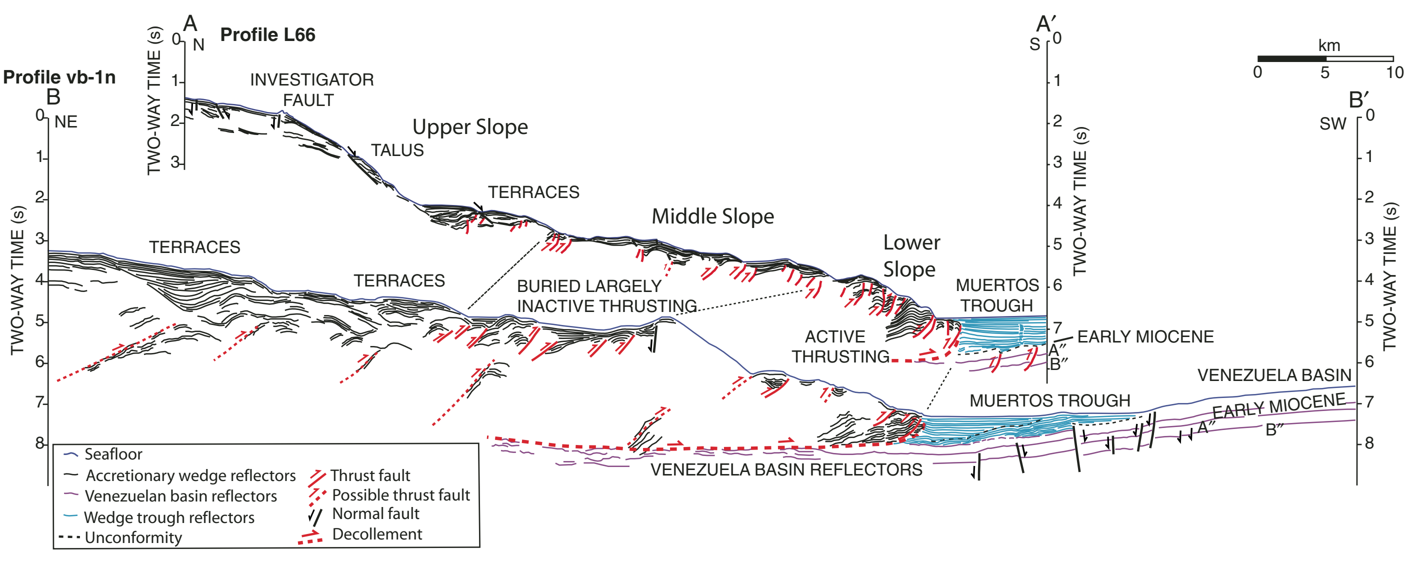

Figure 5. Comparison between line drawing interpretations of the seismic profile L66 (R/V *Pelican*, 2006) across the narrow thrust belt south of Puerto Rico and the reprocessed IG1503 seismic profile vb-1n (Ladd and Watkins, 1979) across the wide thrust belt south of Mona Passage.

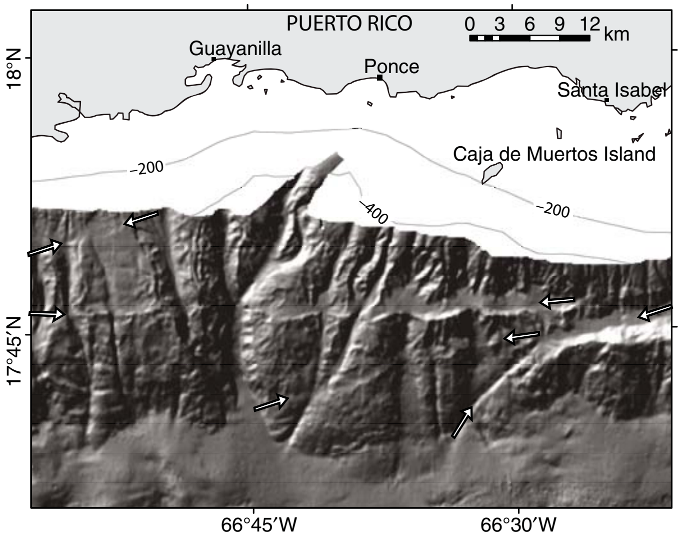

Figure 6. Shaded relief bathymetry, illuminated from northwest, of the Investigator fault area. See Figure 4 for location. Arrows show fault traces. Note the lack of lateral offset of canyon valleys across the fault traces, indicating that the fault system likely accommodates north-south extensional motion, not strike-slip motion.

that the fault instead accommodates a small amount of north-south extension. Third, traces of the Great Southern Puerto Rico fault, in the southern coastal plain of Puerto Rico (Fig. 3), do not cut post-Eocene sediments and thus are not active (Erikson et al., 1990; Glover, 1971).

OBSERVATIONS FROM OTHER ISLAND ARCS

The northeastern Caribbean is not unique in having bivergent thrust geometry. Here, we describe briefly other examples of bivergent thrust belts associated with island arcs. Observations from these examples provide additional constraints on models to explain bivergent thrusting.

Java-Timor

Subduction of the Australia plate occurs along a trench that curves from a north-south trend west of Sumatra to an east-west trend along Banda arc in southeastern Indonesia. Backarc thrusting occurs intermittently along the 1200-km-long segment of this convergent margin east of Java, i.e., north of the eastern Java trench and the Timor Trough (Fig. 2A; Silver et al., 1983). Notably, the backarc thrust belt does not occur north of Java, a crustal block with continental affinity.

An example of backarc thrusting occurs to the north of a line of active volcanoes on the islands of Sumbawa and Flores in the Banda arc (Silver et al., 1986). In this 500-km-long Flores thrust belt, traces of individual thrusts are relatively short (20–30 km long). The 1992 M 7.9 earthquake occurred at the eastern end of this thrust belt, and it had a hypocentral depth of 16 km (Beckers and Lay, 1995). A 300-km-long gap in backarc thrusting occurs to the east of the Flores belt. Backarc thrusting is evident again in the north-verging Alor-Wetar thrust belt. Notably, the Alor-Wetar thrust belt developed where the continental part of the Australian plate has started to move into the subduction zone and where volcanic activity has ceased. Global positioning system (GPS) measurements indicate that most convergence across the plate boundary here currently takes place in the backarc thrust belt (Genrich et al., 1996). Faults of the Alor-Wetar belt are discontinuous and locally trend perpendicular to the slope of the islands rather than perpendicular to the general plate convergence vector (Breen et al., 1989). Arc-parallel strike-slip faults have not been found within the backarc thrust belt, but a strike-slip fault may accommodate some motion between individually moving arc blocks (Breen et al., 1989). The *p*-axes of earthquakes in the backarc are perpendicular to the strike of the trench and are confined to the crust (McCaffrey, 1988).

Northern Panama

Subduction of the Cocos and Nazca plates takes place south of Central America, along a north-dipping zone (Moore and Sender, 1995). Subducting seafloor of the Cocos and Nazca plates has significant relief because it is disrupted by fracture zones as well as by the small spreading ridge that separates the plates. Arc volcanism extends southeastward into western Panama. Subduction may not take place east of longitude 80°W (Westbrook et al., 1995).

The Northern Panama deformed belt is an arcuate thrust belt off the northern shore of Panama and eastern Costa Rica (Fig. 2B; Silver et al., 1995). The trace of folds and faults in the belt generally follows the convex-to-the-north curve of the Panama arc, except at its western end, where it extends on land (Silver et al., 1995; Silver et al., 1990). Overall, the Northern Panama deformed belt verges north, but locally it includes south-verging thrust faults (Reed and Silver, 1995). Earthquakes occur along the length of the belt, indicating that the entire belt is actively deforming. Examples of seismicity include the M_w 7.7 1991 Limon earthquake at the western end of the belt (Suárez et al., 1995), and a devastating tsunamigenic earthquake that took place in the eastern part of the Northern Panama deformed belt in 1882 (Mendoza and Nishenko, 1989). The Limon earthquake occurred at a depth of 24 km, and its *p*-axis was oriented perpendicular to thrust traces in the Northern Panama deformed belt.

GPS measurements and seismic monitoring indicate that the Panama arc is quite rigid and is undergoing relatively little internal deformation (Trenkamp et al., 2002). Kellogg et al. (1995) suggested that the relative motion between the Nazca and Caribbean plates may be fully absorbed by deformation within the Northern Panama deformed belt. However, despite the high strain, there is no indication for a south-dipping subduction zone under Central America (Suárez et al., 1995). Also, strike-slip faults are not abundant within the Northern Panama deformed belt, despite oblique convergence across the Central American arc.

New Hebrides

The 400-km-long segment of the New Hebrides subduction zone that includes the Vanuatu Island group exhibits bivergent deformation (Fig. 2C). Here, seismically active east-verging thrust faults occur east of Vanuatu on the opposite side of the arc from the west-verging accretionary prism that lies between the island arc and the New Hebrides Trench. Notably, the backarc thrusting has developed where the d'Entrecasteaux Ridge is converging with the trench (Geist et al., 1993; Lagabrielle et al., 2003), although the d'Etrecasteaux Ridge is only 100 km wide. Rapid uplift of the easternmost islands in the Vanuatu group shows that the backarc wedge is propagating eastward with time and that most of the convergence between the Australian and Pacific plates of the region is currently taking place in the backarc, not the forearc. The focal mechanism and coseismic uplift of the M_w 7.5 1999 earthquake indicate that faults in the backarc thrust belt extend at least down to a depth of 16–18 km (Lagabrielle et al., 2003).

SANDBOX MODELING OF THE NORTHEASTERN CARIBBEAN

The aforementioned observational data from the northeastern Caribbean, and from other island arcs, demonstrate that thrusting occurs on both sides of some island arcs, that the vergence of backarc thrusting is, overall, opposite to that of forearc thrusting, and that backarc thrust belts tend to contain only frontal thrusts, even where relative plate motions across the volcanic arc are highly oblique. Seismic and geodetic data from the Panama arc also indicate a rigid arc behavior. To gain insight into the factors that may produce such characteristics, we produced simple sandbox kinematic models designed to simulate relative plate motions at a convergent plate boundary with and without a relatively rigid volcanic arc. Next, we provide background information on analog studies of thrust wedges, and then we describe the setup of our models and several geologic situations simulated by our models.

Background: Previous Modeling of Bivergent Thrusting

Sand and numerical models, which assign a noncohesive Coulomb yield criteria to the rheology of the deformed layer, have been used for many years to describe the process of orogen formation (e.g., Davis et al., 1983; Koyi, 1997; Malavieille, 1984; Willett et al., 1993). Such models assume that the crust, or part of the crust, participates in the collision, while the mantle lithosphere subducts (e.g., Beaumont and Quinlan, 1994). In these models, the orogen is a thickened ridge, or "thrust wedge," that forms by faulting and folding of material that lies above a nondeforming substrate. Critical-taper theory shows that the wedge's geometry reflects both the strength of the material in the wedge and the strength of the detachment at the base of the wedge (Davis et al., 1983). Willett et al. (1993) emphasized that wedge shape also depends on isostasy, erosion rates, and the possible presence of an underlying ductile root.

Willett et al. (1993) and Beaumont et al. (1996) produced two-dimensional (2-D) numerical models that simulated the formation of bivergent wedges in cross section. In such models, the crust is represented by a layer of noncohesive Coulomb material spread uniformly over converging rigid plates. During convergence, the downgoing plate slides beneath the overriding plate at a singularity (S). As displacement progresses, a central uplift rises over the singularity, and two thrust belts develop, one on each side of the central uplift (Fig. 1A). On the prowedge side of S, the velocity of the rigid plate is constant (moving toward S), whereas on the retrowedge side of S, the velocity is zero. These boundary conditions give rise to an asymmetry of the bivergent wedge—the prowedge becomes significantly wider than the retrowedge. This asymmetry is also observed in sandbox models (e.g., Fig. 1B). Modeling of flow trajectories in the wedge indicates that material first moves toward S and then up into the axial uplift zone and the retrowedge. In real continental collisional orogens, this motion contributes to transportation of metamorphic rocks, formed at depth, up to Earth's surface (e.g., Platt, 1986). Beaumont and Quinlan (1994, their p. 760) compared sandbox model results (e.g., Malavielle, 1984) to the results of their numerical model and stated that it "shows the same deformation style." Thus, analog models, which employ sand as a laboratory-scale proxy for the crust, can provide insight into the kinematics and geometry of thrust-wedge development.

Most subduction zones are associated with oblique convergence, and thus study of their kinematics requires analysis of transpression in three dimensions (3-D). Oblique convergence in orogens may be accommodated by strain partitioning, in which the regional motion divides into a component of subperpendicular slip (thrust faulting) at the trench and a component of strike-slip faulting and/or block rotation in the forearc and arc (e.g., Beck, 1982; Pinet and Cobbold, 1992; Tikoff and Teyssier, 1994; McCaffrey, 1994). Oblique convergence has been addressed in computer models (Braun and Beaumont, 1995; Vernant and Chéry, 2006) and sandbox models (e.g., Pinet and Cobbold, 1992; McClay et al., 2004). Although some of the sand in the bivergent wedge produced in their model moves toward the retrowedge, the faults across the entire deformed region (including the retrowedge) verge to the prowedge side (McClay et al., 2004; Fig. 1B). With increasing obliquity of convergence, strike-slip faults form at the center of the sand wedge, and the wedge becomes more symmetric.

Model Setup and Strategy

Sandbox models can be built with varying levels of sophistication (e.g., Malavieille, 1984; Marques and Cobbold, 2002; McClay et al., 2004). The most advanced models use servomotors to provide constant strain rates, deform a sand layer in which alternating layers of different-colored sand represent bedding in the upper crust, and/or place the sand on a substrate of silicon putty to provide an appropriately scaled analog for plastically deforming lithosphere (e.g., Davy and Cobbold, 1991; Pinet and Cobbold, 1992; Pubellier and Cobbold, 1996; Marques and Cobbold, 2002; McClay et al., 2004). Our study utilizes the simplest possible model configuration—we deformed an unstratified sand layer without a substrate of plastic material and without a servo-controlled driver. In map-view, our model is approximately six orders of magnitude smaller than the northeastern Caribbean. However, the thickness of the sand in our model is 2–3 cm, and if scaled up by six orders of magnitudes, will represent the entire crust, not just the sedimentary layer, which is rheologically inappropriate. Thus, we do not intend for our models to be viewed as "scale models" in the sense that the sand can be considered to be a rheological proxy for the crust. Rather, we consider our models to be simply kinematic representations, the sole purpose of which is to provide visual map-view insight into the relative movements among different components of the modeled system, the overall distribution of faults, and the overall slip direction on faults. The simplicity of our model design made it possible to set up experimental runs very quickly, and it allowed us to examine the consequences of many different kinematic configurations. Despite its simplicity, our apparatus yields similar results, geometrically, to those produced using a sophisticated driving apparatus and rigorously scaled materials (cf. Pinet and Cobbold, 1992; McClay et al., 2004).

Our sandbox apparatus consists of a wooden base (120 cm × 90 cm) surrounded by Plexiglas walls that are 25 cm high (Fig. 7A). At a distance of 46 cm from one end of the box, we cut a 60-cm-long slit through the floor of the box. This "exit slit," which represents the kinematic singularity of Willett et al. (1993), is parallel to the ends of the box. For ease of comparison with features of the northeast Caribbean region, we will henceforth refer to the end closer to the exit slit as the "south end" of the box and the other end as the "north end" (Fig. 7A). We placed a 3-cm-wide by 65-cm-long Mylar flap over the exit slit and taped it on the south side to keep sand from spilling through the slit. Next, we ran a Mylar transport sheet along the floor of the box, beneath the flap, and through the exit slit. We buried the transport sheet with a layer of sieved sand (18 mesh) smoothed to a uniform thickness (2 cm to 3 cm thick). In order to make

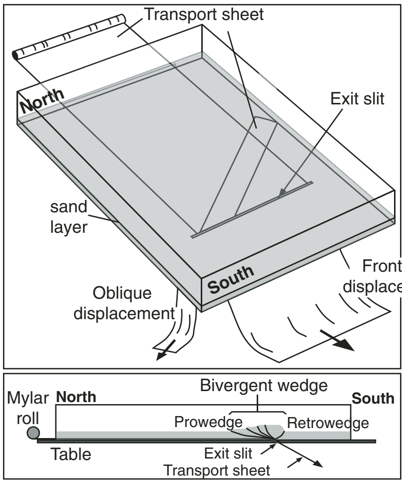

Figure 7. Schematic diagram of the simple sandbox modeling apparatus. Top: Oblique view, showing the position of the exit slit, and the configuration of Mylar transport sheets for simulating frontal convergence and oblique convergence. Bottom: Cross-section view, showing the position of the prowedge and retrowedge relative to the exit slit. "North" and "south" are used for ease of reference.

thrust traces stand out better during experimental runs, we moistened the sand very slightly to produce a slight amount of cohesion. With the edge of a ruler, we made spaced linear indentations on the surface of the sand, providing a visible grid that allowed us to track the amount of shortening in the direction perpendicular to the slit and the amount of strike-slip parallel to the exit slit.

To generate deformation of the sand layer, we slowly pulled the sheet southward, through the exit slit from beneath the box. For perpendicular convergence models, we used a 200-cm-long transport sheet. For oblique-convergence models, we used a narrower Mylar transport sheet (30 cm wide) and oriented it at an angle to the exit slit before passing it through the slit; the narrower width was necessary to fit the width of the slit. In a number of experiments, we simulated the consequences of having a relatively rigid crustal block within the bivergent wedge. Our blocks, which symbolized Puerto Rico and eastern Hispaniola, consisted of 16 × 6 × 5 cm and 17 × 8 × 5 cm sand-filled cardboard boxes. The boxes were placed on top of the flap covering the exit slit and were surrounded by the sand layer. Finally, to investigate the consequences of differential displacement of the backstop and of interaction with obstacles in the foreland, we displaced a rigid block toward the foreland to generate a monovergent thrust wedge. Next, we describe our experimental runs.

Case 1: Frontal Wedge, Without a Rigid Block

To simulate a frontal wedge, we pulled the transport sheet slowly to the south, through the exit slit. The nonmoving sand forms an effective backstop that prevents the sand on the transport sheet from moving past the slit, because as the wedge thickens, gravitational loading strengthens the sand in the wedge as required by Byerlee's law of friction. Thus, as the wedge of thickened sand gets wider, the effective position of the backstop moves to the foreland (Fig. 8A; Fig. A1[1]). As observed by previous researchers (e.g., Malavieille, 1984; McClay et al., 2004; Storti et al., 2001), the resulting bivergent wedge is asymmetric. Continued convergence builds a succession of slit-parallel thrusts on the north side of the slit, resulting in a prowedge that tapers gently to the north. On the south slide of the slit, a single obvious thrust trace develops, and the retrowedge is relatively narrow. This trace bounds a steep escarpment that undergoes constant slumping during the experiment.

Case 2: Oblique Wedge, Without a Rigid Block

If the convergence vector trends at N35°E relative to the slit, displacement of the Mylar transport sheet results in transpression with a sinistral strike-slip component (Figs. 8C and 8E). Significantly, the initial bivergent wedge that develops trends parallel to the exit slit, as was observed by McClay et al. (2004). On the north side of the slit, left-lateral shear develops penetratively across the wedge, as indicated by distortion of the surface grid lines. As a consequence, sand moves progressively toward the west end of the slit. The excess volume of sand causes the thrust-wedge width to increase along the west edge of the slit, relative to the east edge, so the leading edge of the prowedge rotates progressively clockwise with the growth of each successive thrust until the leading edge of the wedge becomes perpendicular to the convergence direction (Fig. 8C; Fig. A1 [see footnote 1]). At this point, further growth of the prowedge ignores the orientation of the original exit slit. This phenomenon does not happen on the retrowedge side because a significant strike-slip component of displacement does not transfer across the slit. At a very low angle of convergence, the sand wedge develops into a positive flower structure (Fig. A1 [see footnote 1]), as was also noted by Richard and Cobbold (1990) and McClay et al. (2004).

Case 3: Frontal Displacement, With a Rigid Block

To simulate the existence of a rigid island arc, we placed a sand-filled cardboard box on top of the Mylar flap above the subduction slit and surrounded the box with sand. Upon pulling the transport sheet through the slit, the prowedge develops in front of the rigid block, with a shape and taper identical to that which develops without the block (Fig. 8B). When the block is present, the forearc face of the block serves the role of a backstop. Notably, in contrast to runs with no backstop (case 1), progressive deformation with the backstop present leads to the development of a wider retrowedge consisting of distinct imbricate thrust slices (cf. Figs. 8B and Fig. 8A). This happens because the backarc face of the block also acts as a rigid backstop, which pushes toward the backarc. Nevertheless, the retrowedge remains narrower than the prowedge.

Case 4: Oblique Displacement, With a Rigid Block

The setup for this experiment was identical to that of case 3, except that the transport sheet was moved obliquely, at a moderate angle (30°) to the subduction slit. In this case, a component of left-lateral shear affects the prowedge, and sand is transported to the west edge of the block (Figs. 8D and 8F). As in case 2, successive thrust sheets are wider at the west end of the prowedge than at the east end. As the prowedge grows, the strike of the leading thrust rotates clockwise until it becomes perpendicular to the transport direction. In the backarc region, a retrowedge containing imbricate thrusts grows. Transport direction in the retrowedge is generally almost perpendicular to the face of the rigid block. In runs where the block rotates counterclockwise slightly (presumably due to the push of excess sand on the western end of the prowedge), the retrowedge is wider to the west (Figs. 8D and 8F). There is no shear zone in the retrowedge. This observation suggests that the strike-slip component of deformation in this run was taken up entirely in prowedge deformation. Retrowedge deformation was due solely to the push of the rigid block toward the backarc.

[1]GSA Data Repository item 2009115, Additional sandbox models of oblique convergence show the development of sedimentary wedges above a subduction zone with time and with changing convergence angles, is available at http://www.geosociety.org/pubs/ft2009.htm or by request to editing@geosociety.org.

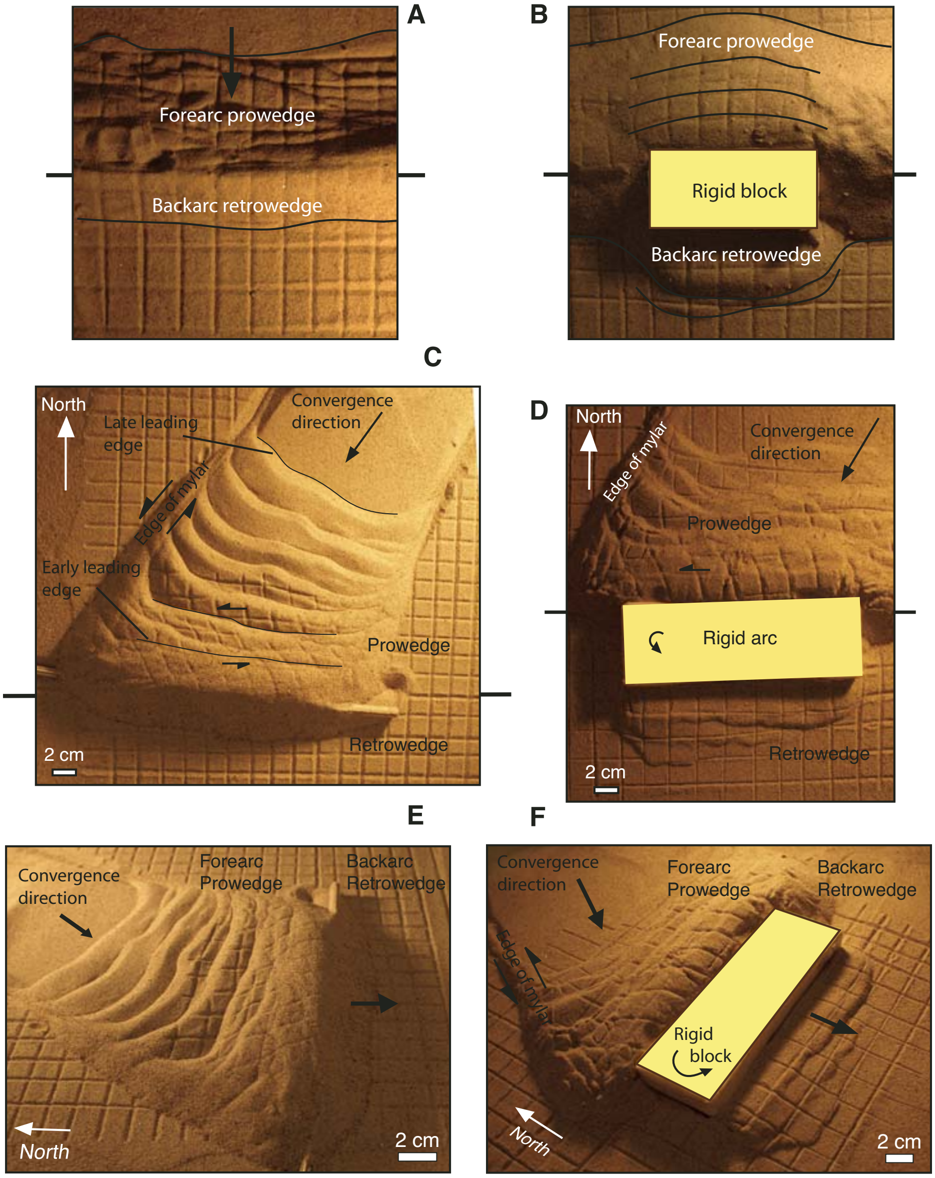

Figure 8. Comparison between bivergent wedge deformation in models with and without a rigid block. (A) Map view of a frontal bivergent wedge consisting of sand only. Arrow indicates convergence direction. The retrowedge does not contain visible imbricates. (B) Map view of a bivergent wedge formed in the presence of a rigid block (yellow rectangle). Distinct imbricates have developed in the retrowedge. (C) Map view of a bivergent wedge forming during oblique convergence. The retrowedge does not contain visible imbricates. (D) Map view of a bivergent wedge during oblique convergence in the presence of a rigid block. Because of mass accumulation at the west end of the block, there is a slight rotation of the block. Distinct imbricates have formed on the retrowedge side, and the width of the retrowedge decreases slightly to the east. E and F are same as C and D but in oblique view.

Case 5: Colliding Rigid Blocks (Frontal and Oblique)

The northeastern Caribbean plate boundary changes from being an oblique subduction zone in the east (from the Virgin Islands, across Puerto Rico, and across the front of eastern Hispaniola) into a collisional boundary in the west (from central Hispaniola westward). The collisional boundary results from the impingement of the Greater Antilles arc against the Bahamas Platform. To simulate this situation, we placed two narrow rigid blocks, representing components of the Greater Antilles arc (Hispaniola and Puerto Rico), above the Mylar flap over the subduction slit, and we placed a broad rigid block (representing the Bahamas Platform) on the transport sheet. When the transport sheet was pulled, the "Bahamas block" collided with the western arc block (Figs. 9A and 9B).

In cases where the transport sheet moves perpendicular to the subduction slit (i.e., frontal convergence), the collision leads to a distinct along-strike change in the character of the retrowedge. Specifically, the retrowedge is wider and thicker on the south side of the arc block impacted by the "Bahamas block" than on the south side of the block that is not involved in the collision. Notably, the southernmost thrust of the retrowedge grows eastward in front of the block that is not involved in the collision. In experimental runs that utilized an obliquely converging wedge, the collision resulted in rotation of the western block, and this caused even more widening of the retrowedge behind the rotating block.

Case 6: Presence of an Obstacle in Front of the Retrowedge

The Beata Ridge of the northeastern Caribbean region acts as a basement high in the foreland of the retrowedge. We simulated the impingement of the Muertos thrust system with the Beata Ridge by placing a rigid block in front of a thrust wedge produced by pushing another rigid block to the foreland through a sand layer. When the thrust wedge reaches the obstacle, preexisting thrust traces are oroclinally bent, and new thrusts initiate with a distinct curve toward the point of collision (Fig. 9C). The result is a syntaxial curve in the thrust wedge (cf. Paulsen and Marshak, 1999).

DISCUSSION

What causes the growth of thrust belts on both sides of an island arc, such as occurs in the northeastern Caribbean? Next, we first review previous hypotheses used to explain island-arc thrusting geometries, and then we use our observations and our modeling results to evaluate these hypotheses and suggest our own interpretation.

Previous Explanations for Bivergent Thrusting along Island Arcs

Several mechanisms have been proposed as explanations for bivergent thrusting in island arcs. We describe some of these here. Of these, two attribute backarc thrusting to phenomena happening in the asthenospheric mantle, and three attribute backarc thrusting

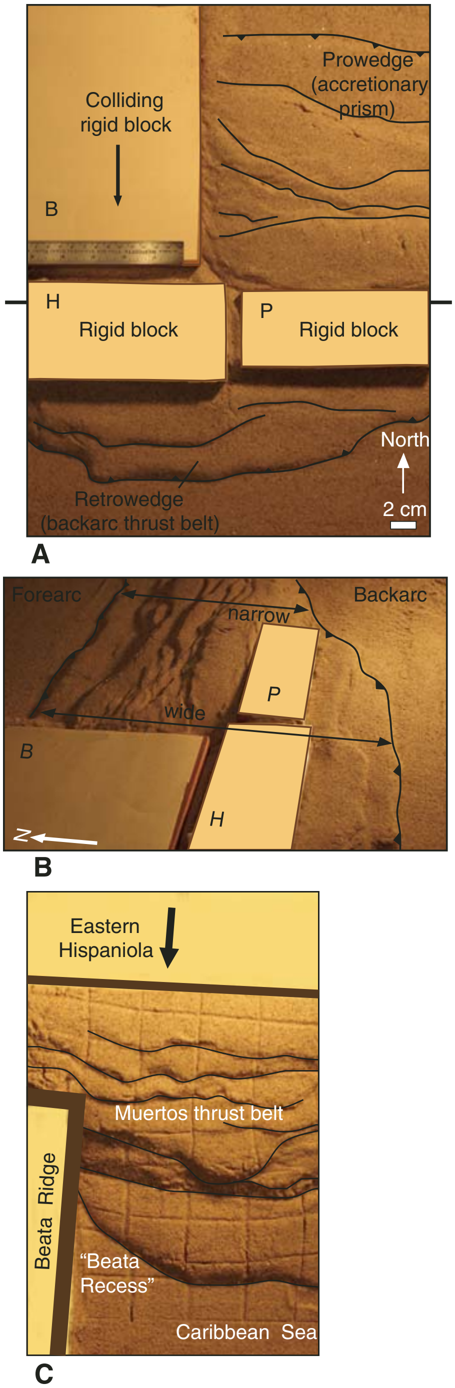

Figure 9. Collision of a rigid block with the prowedge. (A) In this model, block H and block P represent rigid blocks within the bivergent wedge. Collision of a rigid block (block B) with block H causes block H to move toward the backarc relative to block P. As a result, the retrowedge is wider along block H than it is along block P. (B) An oblique view of the image in A, emphasizing the along-strike widening of the retrowedge due to the partial collision in the prowedge. (C) In a sandbox model, the Beata Ridge can be represented as an obstacle or an indenter that lies in the foreland of the Muertos thrust belt. As a result, thrust traces of the belt curve into the edge of the ridge.

to phenomena happening within the crust and/or lithospheric mantle.

(1) Subduction Reversal: Dewey and Bird (1970), Pinet and Cobbold (1992), and Pubellier and Cobbold (1996) suggested that subduction reversal occurs when a buoyant crustal block collides with a continent after an intervening oceanic basin has been consumed. In this view, the original downgoing slab breaks off, and the original overriding plate bends down and begins to sink into the mantle. This model has been applied to explain backarc thrusting in northern New Guinea (Cooper and Taylor, 1988).

(2) Basal Traction: Conrad et al. (2004) suggested that trench-directed asthenospheric flow develops at the base of the overriding plate in response to symmetrical suction from the downgoing slab in cases where slab-pull forces are only weakly transmitted to the subducting plate at the surface. Backarc thrusting is caused in this framework by traction applied to the base of the overriding lithosphere by flowing asthenosphere.

(3) Magmatic Inflation: Hamilton (1979) argued that intrusion of plutons "inflates" volcanic arcs, causing displacement of both arc margins sideways, by thrusting on both sides of the arc.

(4) Gravitational Spreading: Silver et al. (1983) and Breen et al. (1989) suggested that thickening of the crust in the Java-Timor arc eventually led to gravitational spreading (i.e., extensional collapse), which produced movement of the sides of the arc outward. According to this concept, the movement would be accommodated by slip on thrust faults that develop at the base of the slope, where compressive stress is presumed to be greatest (Dalmayrac and Molnar, 1981).

(5) Collision with Buoyant Crust: Hamilton (1979) and Silver et al. (1983) suggested that a backarc thrust belt develops when buoyant crust arrives at a subduction zone, as is happening at the Australia-Timor arc boundary. Geist et al. (1993) explored this concept by using a thin viscous-sheet model to predict the stress field within island-arc lithosphere resulting from impingement of a buoyant oblique ridge. They found that the collision produced transpression in the forearc and predominantly arc-perpendicular compression in the backarc. Beaumont et al. (1996) presented numerical models suggesting that a retrowedge *only* develops when a buoyant slab moves into the subduction system.

Inferences from Observations of the Northeastern Caribbean

Byrne et al. (1985) suggested that backarc thrusting in the northeastern Caribbean is due to active northward subduction of the Caribbean plate beneath the eastern Greater Antilles. Their proposal was based on the location of an M_s 6.7 earthquake at a depth of 32 km on a gently northward-dipping fault south of the Dominican Republic (star in Fig. 3), on the location of two deeper events associated with similar or more steeply dipping fault planes, and on the observation that a continuous reflector extends from the trough for ~40 km under the Muertos thrust belt (Ladd and Watkins, 1979). The interpretation of the Muertos thrust belt as a subduction zone, and thus the Muertos Trough as a trench, has been explicitly or implicitly accepted in the literature during the past 20 years in papers dealing with the northeastern Caribbean (Dillon et al., 1996; Dolan et al., 1998; Driscoll and Diebold, 1998; Manaker et al., 2008; Mann et al., 2002; McCann, 2007; van Gestel et al., 1998). We argue that this interpretation is problematic for two reasons.

First, since true subduction is driven by a slab's negative buoyancy within the upper mantle, there must be sufficient room in the mantle for a plate to sink before the process can begin. The distance between the Puerto Rico and Hispaniola Trenches on the north side of the Eastern Greater Antilles island arc and the Muertos Trough on the south side is only 235 km (Fig. 3). Considering the age of the subducting North American plate (85–125 Ma; Mueller et al., 2008) and that of the subducting Caribbean plate (100–120 Ma; Mueller et al., 2008), both slabs should be 90–100 km thick. Further, seismic observations (Dolan and Wald, 1998; Ladd and Watkins, 1979; ten Brink, 2005) show that the North American and Caribbean plates dip at 10° to 20° within 30 km inland of the Puerto Rico Trench and Muertos Trough, respectively. Thus, there is simply too little room for true simultaneous subduction of two plates with opposite polarities under the Eastern Greater Antilles arc. Recognizing this problem, Dillon et al. (1996), Dolan et al. (1998), Mann et al. (2002), and van Gestel et al. (1998) envisioned direct contact between the downgoing North American and Caribbean slabs at subcrustal depth beneath the island arc. However, it is not clear why Caribbean subduction is sustained if such contact exists.

Second, the kinematics of deformation within the Muertos thrust belt are not compatible with true subduction along the boundary. Specifically, if the Caribbean plate interior were subducting under the Eastern Greater Antilles arc, the convergence direction would be highly oblique to the strike of the Muertos Trough, based on GPS measurements (Manaker et al., 2008; Mann et al., 2005). Such oblique convergence would have to be accommodated either by oblique thrusting within the Muertos belt, or by partitioning between frontal thrusting and strike-slip faulting in the Muertos belt and adjacent onshore portions of the eastern Greater Antilles. As described earlier in this paper, the salients of the Muertos deformation front indicate that the belt is a zone of dip-slip thrusting, and that there are no active zones of strike-slip faulting within the Muertos thrust belt or along the south shore of the arc.

Finally, the physical conditions and the work necessary for subduction initiation are still not well constrained, and therefore, even if the subducted lithosphere of the North American plate were to break off, it is not clear that loading by the Muertos thrust belt may succeed in pushing the plate down into the asthenosphere, thus triggering the process.

The tectonic history of the Eastern Greater Antilles arc is also incompatible with the proposal that magmatic inflation drives the development of bivergent thrust belts. Volcanic activity has not happened in Puerto Rico and Hispaniola during the past 30 Ma or more, a period during which thrusting has continued in the retrowedge.

Inferences from Observations of Other Island Arcs

Observations from other backarc thrust belts lead us to conclude that shear tractions beneath the overlying plate, as suggested by Conrad et al. (2004), are not responsible for the observed retrowedges. First, if shear traction occurred due to subduction, retrowedges should occur along the entire length of the arc. They do not. For example, only the 400-km-long Vanuatu segment of the convergent boundary in the New Hebrides subduction zone includes a retrowedge (Lagabrielle et al., 2003), and in the Banda arc, a 300-km-long gap exists between the Flores and Alor-Wetar retrowedges (Silver et al., 1983). Second, if the formation of the retrowedge were a consequence of shear tractions related to subduction, then the kinematics of deformation in the wedge should reflect the obliquity of the convergence. It does not. For example, in the Muertos thrust belt, there is no strike-slip deformation despite the oblique direction of plate convergence.

Our work does not rule out the possibility that gravitational spreading could locally add to the compressional stress at the base of the thrust belt (Silver et al., 1983; Breen et al., 1989). We doubt, however, that it serves as the primary driver for the development of bivergent thrust belts, for if it did, retrowedges would form behind all arcs and along their entire lengths, and they do not.

Inferences from Sandbox Models

Our simple sandbox analog models demonstrate the following key points about the development of thrust wedges involving island arcs:

Pulling a sand-laden Mylar sheet through an exit slit in a sandbox to simulate “subduction” leads to the development of a bivergent wedge. If the deformation involves only sand, the retrowedge is narrow. The addition of a rigid block above the subduction slit results in a widening of the retrowedge, and the development of upward imbricate thrusts, with vergence opposite to that of the subduction direction, in the retrowedge. This observation implies that significant growth of retrowedges occurs only when the strength of an island arc is sufficient to transmit stress to the backarc region. Application of this concept to the northeastern Caribbean suggests that the inactive Eastern Greater Antilles arc is stronger than the sediment being incorporated in its marginal thrust wedges, so subduction of the North American plate produces compressive stress that is transmitted through the arc to drive the development of thrusts in the Muertos thrust belt of the backarc (Fig. 10).

In sandbox models in which a rigid block lies over the exit slit, the retrowedge consists dominantly of frontal thrusts and does not accommodate a strike-slip component of strain. Rather, strike-slip deformation is concentrated in the forearc. We found a similar distribution of faulting in the island-arc systems that we examined. The observation implies that the backarc thrust belt is driven by the displacement of the arc block toward the backarc.

The collision of a buoyant block with one part of a rigid arc pushes that portion farther toward the backarc region. As a result, the retrowedge is wider and thicker behind the colliding portion of the arc than behind the part where only subduction occurs (Figs. 9A and 9B). This model, therefore, suggests that the development of a wider retrowedge south of Hispaniola than south of Puerto Rico reflects the collision of the buoyant Bahamas Platform with Hispaniola (Fig. 10). Previous models suggesting that greater sediment thickness leads to widening of a thrust wedge (e.g., Marshak, 2004) cannot explain the difference in the width of the retrowedge along the Muertos Trough—the retrowedge south of the Dominican Republic is wider and thicker than south of Puerto Rico, yet sediments in the Muertos Trough are thicker south of Puerto Rico than south of the Dominican Republic (Fig. 5). Oblique convergence may result in rotation of an arc block, leading to additional widening of the backarc thrust wedge. Changes in width and orientation of the retrowedge along strike are seen in the Wetar, Alor, North Panama, and Muertos backarcs. In the Muertos thrust belt, the orientation of the partially buried thrust system in the Middle Slope Province may indicate clockwise rotation since this portion of the thrust belt was active (purple line in Fig. 4).

Collision of the retrowedge with an obstacle to its foreland may generate map-view curvature in the thrust wedge. An example is the northward curvature of the western end of Muertos Trough, where the Beata Ridge serves as an obstacle to the southward motion of Hispaniola (Fig. 10).

Implications of Retrowedge Formation for Arc Rigidity

Simple sandbox models simulating the kinematics of a bivergent thrust wedge mimic the development of a retrowedge along oceanic island arcs most successfully when a rigid block is placed over the subduction slit, thus implying that the existence of a backarc thrust belt may be evidence that the adjacent arc is, indeed, relatively rigid. Observations of a rigid arc in Panama support this association (Trenkamp et al., 2002). Growth of the prowedge appears to apply horizontal compression to the block, driving it into the sediment of the backarc, causing the backarc side of the block to act effectively as a backstop. Unlike orogenic belt models (e.g., Willett et al., 1993), material is not translated from the forearc into the arc and backarc region and is not exhumed from deep within the crust.

The rigidity of oceanic island arcs may be attributable to their dominantly mafic composition—oceanic island arcs are composed primarily of oceanic crust and mafic and ultramafic volcanics and intrusives (Shillington et al., 2004). Not all island arcs behave rigidly. For example, the Japan arc contains many active thrust faults whose vergence is often similar to the subduction zone, indicating that the arc is deforming internally (Okamura et al., 2007). The weakness of the crust there may be due to the occurrence of intermediate and felsic crust in the arc, because the arc originated as a continental-crustal sliver.

Role of Colliding Buoyant Crust in Retrowedge Development

The mechanical conditions for the development of a bivergent wedge in island arcs are not entirely clear. Beaumont et al. (1996) suggested

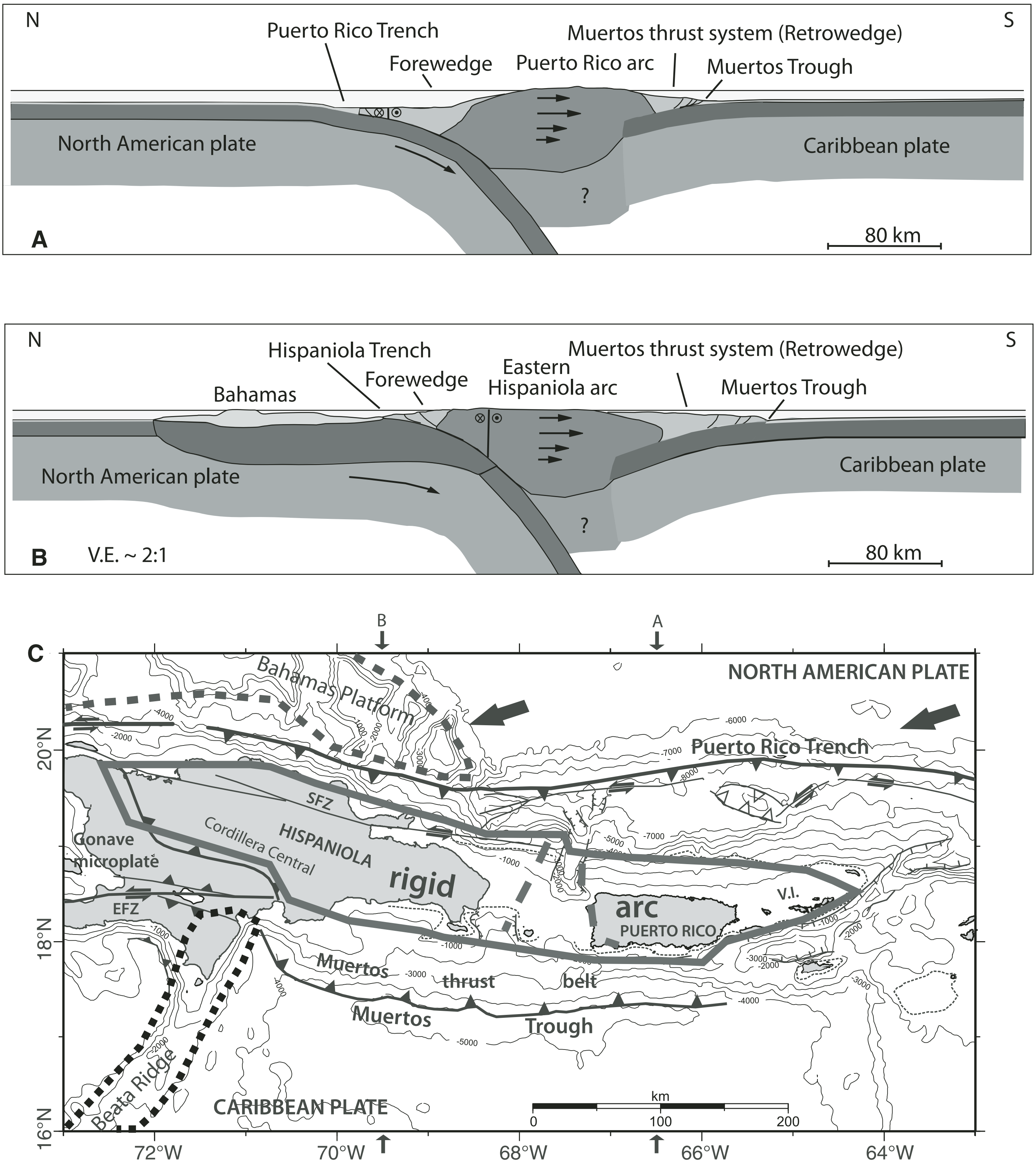

Figure 10. Conceptual tectonic cross sections across the North American–Caribbean plate boundary in (A) Puerto Rico and (B) Hispaniola. Location of cross sections and major elements are shown in map view. (C) Minor intra-arc deformation is observed in the area enclosed by dashed grey lines. VI—Virgin Islands, V.E.—vertical exaggeration.

that bivergent wedges in continental orogens only begin to develop when relative buoyant crust moves into the subduction zone and is thrust beneath the edge of the overriding plate. The relatively buoyant crust can be a continental margin, an aseismic ridge, or an oceanic plateau. Some bivergent island arc systems have developed adjacent to the subduction of an aseismic ridge (d'Entrecasteaux Ridge near Vanuatu; Fig. 2C), a thick plateau (the Bahamas Platform next to Hispaniola; Fig. 3), or a continental margin (the Wetar thrust near the Timor Trench; Fig. 2A); hence, increased buoyancy of the subducting lithosphere must play a role in the development of bivergent wedges in island arcs (Silver et al., 1983). However, some active bivergent wedges have developed next to subduction zones where the seafloor is smooth and deep. Examples include the bivergent wedge of Puerto Rico, where the Puerto Rico Trench is unusually deep (Fig. 3; ten Brink, 2005), the Flores backarc thrust, which forms along a portion of the island arc where a smooth abyssal plain is subducting into the Java Trench (Fig. 2A), and the Northern Panama deformed belt east of 80°W (Fig. 2B). One explanation for these observations is that oceanic island compressive stresses are distributed laterally within the rigid arc and therefore are transmitted to the backarc region over a much wider region than the region being impacted directly by a buoyant subducting lithosphere. Observations and modeling of the Tonga and New Hebrides arcs show the effect of ridge impingement (Louisville and d'Entrecasteaux Ridges, respectively) to extend along ~500 km of the arc (Geist et al., 1993).

Implications for Seismic and Tsunami Hazards with Emphasis on the Northeastern Caribbean

Earthquake hazard from forearc and arc faulting is commonly greater than that from subduction zone earthquakes because of the closer proximity of near-island faults to population centers. Seismic hazard is expected to be low from thrust faults within oceanic island arcs because of the paucity of these faults within the rigid arc. This is in contrast to continental arcs, such as Japan, where moderately large thrust earthquakes are common within the arc (e.g., Okamura et al., 2007).

Retrowedges appear to be dominantly zones of dip-slip thrusting, even along plate margins at which oblique convergence is occurring, and thus they do not contain abundant strike-slip faults. Although strike-slip earthquakes are not expected in retrowedges, large shallow dip-slip earthquakes do take place there, as evidenced by the 1991 M 7.7 Limon, the 1999 M 7.5 Vanuatu, and the 1992 M 7.9 Flores earthquakes. These earthquakes occur at crustal depths beneath the retrowedge, and, depending on the width of the deforming retrowedge, they can be destructive. They can also generate devastating tsunamis, as happened during the Flores 1992, Vanuatu 1999, and the San Blas (Panama) 1882 earthquakes.

South of Puerto Rico, the belt of active thrust faults, including occasional buried thrusts within the Muertos Trough, is only ~20 km wide. The narrow retrowedge there suggests either a small amount of compression has been transmitted across the island arc, or that compression started only recently. The former explanation is in agreement with previous modeling inferences for low degree of coupling across the subduction interface of the Puerto Rico Trench (ten Brink and Lin, 2004). Contrary to a recent assessment (McCann, 2007), the narrow width of the retrowedge limits the downdip width of the potential rupture area and, hence, limits the magnitude of potential earthquakes. There is indeed no historical record of large earthquakes south of Puerto Rico. The zone of active thrusting widens significantly south of Hispaniola. Thus, it is more likely that large earthquakes could happen there because of the wide downdip extent of the detachment fault (Fig. 10). If the entire 170-km-long backarc thrust belt south of the Dominican Republic ruptured, it could produce an M 7.8 earthquake, assuming a downdip width of 45 km and a slip of 3 m. Examples of backarc thrust earthquakes in this region include the 1984 M_s 6.7, and perhaps the destructive 1751 Hispaniola earthquake (Byrne et al., 1985).

CONCLUSIONS

The development of thrust belts on both sides of some oceanic island arcs (where the vergence of each thrust system is primarily away from the arc axis) is best explained by a model in which the arc and the bordering thrust belts constitute a bivergent crustal wedge. Therefore, the backarc thrust belt is interpreted to be a retrowedge, and it does not indicate a reversal of subduction polarity or mantle-driven trenchward motion of the overriding plate. Oceanic island arcs act as relatively rigid blocks, where coherent motion toward the backarc produces imbricate thrust systems in the backarc. These arcs may be rigid because of their mafic composition. The rigid arc concept may help to explain why the strike-slip component of oblique convergence is accommodated entirely in the forearc and frontal arc, while the backarc is dominantly a dip-slip thrust belt, and why thrust faults are relatively rare within these arcs. Although sandbox models generate backarc imbricate thrusts even in the absence of arc collision with a buoyant block, observed backarc thrusting around the globe may be initiated by the impact of a buoyant subducting lithosphere with a prowedge. Notably however, the affected region can extend, in the direction parallel to the arc axis, beyond the region of impact, perhaps because compressive stresses are also distributed laterally within the rigid arc.

In the case of the northeastern Caribbean, we consider the Muertos thrust belt south of Puerto Rico and eastern Hispaniola to be a retrowedge, formed by cross-arc transmission of stress generated by the subduction of the North American plate, and by the collision of the Bahamas Platform with Hispaniola. In detail, the geometry of this wedge reflects differential block movement of the Hispaniola arc relative to the Puerto Rico arc and the impingement of the Beata Ridge against the Hispaniola arc.

ACKNOWLEDGMENTS

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